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The initial scope of this program was to develop ultra-low-resistivity GaAs-based materials for application to Npn and Pnp AlGaAs/GaAs heterojunction bipolar transistors (HBTs). Due to early success in the program and to complement research and development activities at the U.S. Army EPSD laboratory in Ft. Monmouth, NJ, the program scope was expanded to include photonic applications of HBTs including photodetector optical receivers and monolithic integration of PIN and HBT devices for high performance receivers.

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Study of Ultra-Low Resistivity Material for Monolithically Integrated Npn and Pnp AlGaAs/GaAs Heterojunction Bipolar Transistors

Final Report

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TABLE OF CONTENTS

1.0 STATEMENT OF THE PROBLEM STUDIED

The initial scope of this program was to develop ultra-low-resistivity GaAs-based materials for application to Npn and Pnp AlGaAs/GaAs heterojunction bipolar transistors (HBTs). Due to early success in the program and to complement research and development activities at the U.S. Army EPSD laboratory in Ft. Monmouth, NJ, the program scope was expanded to include photonic applications of HBTs including photodetector optical receivers and monolithic integration of PIN and HBT devices for high performance receivers.

2.0 SUMMARY OF MOST IMPORTANT RESULTS

2.1 Ultra-Low Resistivity n-Type GaAs for Pnp HBTs

The growth of ultra-low resistivity (ULR) n-type GaAs and it's application to HBTs was investigated. A sharp decrease in lifetime was observed for carrier concentrations over 5 x 10^{18} cm^{-3} as indicated by a sharp drop in photoluminescence efficiency in bulk material and Pnp current gain. For Pnp HBT applications, a base doping ~ 8 x 10^{18} cm^{-3} was found to be an optimum compromise between low resistivity and high minority carrier lifetime. At this base doping, a common emitter current gain of 10, f_T of 33 GHz and f_{max} of 66 GHz were obtained with a 2.0 x 4.0 μm^2 emitter self-aligned device. This mm-wave performance for AlGaAs/GaAs Pnp HBTs was a record for any electronic device reliant on hole transport.

This demonstration of Pnp mm-Wave performance was only possible with the development of ULR n-type GaAs with reasonable lifetime. The existence of this high frequency Pnp technology will impact III/V microelectronics by enabling high-speed, high efficiency and low-power dissipation complementary HBT circuits. These circuits have broad application to high-speed logic, high-power and high-efficiency amplifiers, analog-to-digital converters, and OEICs.

2.2 Ultra-Low Resistivity n-Type GaAs for Npn HBTs

The growth of ULR n-type GaAs was also applied to minimizing Npn emitter resistance and improving it's uniformity and scalability. This was achieved with a non-spiking PdGe contact to n^+ GaAs with contact resistivity ~ 10^{-7} ohm-cm^2. This contact was shown to be uniform, reproducible and not subject to strain-related reliability issues associated with conventional InGaAs emitter caps. Npn HBTs with a significant increase in current density capability and improvement in turn-on voltage uniformity demonstrated f_T ~ 60 GHz and f_{max} ~ 150 GHz for a 2.6 x 5.2 um^2 emitter self-aligned device. The application of this contact scheme to high-speed logic, analog-to-digital converters, high efficiency microwave and millimeter wave power applications, and optoelectronic integrated circuits, is expected to yield improved frequency performance and uniformity.

2.3 1.3 μm GaAs-Based Optoelectronic Integrated Circuits

$Ga_{0.65}In_{0.35}As$ PIN photodetectors were monolithically integrated with GaAs-based HBTs for high-performance, GaAs-based 1.3 μm OEICs by selective

organometallic vapor phase epitaxial growth of a 1.3 micron wavelength PIN photodetector on GaAs. Less than 2 $\mu A/um^2$ at -9.0 V was obtained with a 5 micron step graded buffer (seven percent InAs per micron). The optical responsivity was ~ 0.1 mA/mW at 1.3 microns with a 0.6 micron PIN depletion width assuming no surface reflection.

The integration of 1.3 micron OEICs on GaAs substrates is broadly applicable to achieving low-cost high-performance OIECs by combining optical fiber compatibility with GaAs substrate maturity.

2.4 High Speed HBT Photodetectors

Collaborations between RTI and EPSD during this program resulted in a novel approach to achieving high speed HBT phototransistors. Previous phototransistors were designed to detect incident light normal to the surface. This typically requires a large area annular emitter contact for absorbtion which results in poor high frequency performance. An invention in this program which avoids this limitation detects incident light parallel to the surface and along the entire length of the device. This allows narrow emitter geometries to be used for optimum f_T and f_{max} performance. Initial results have demonstrated responsivities comparable to that achieved with MSMs without correcting for a greatly reduced illumination efficiency. A joint U.S. Army and RTI patent was filed on this invention.

These HBT phototransistor was fabricated at RTI and tested at EPSD. The measured photoresponse of these devices was limited by the laser bandwidth which was 10 GHz. This approach to high-speed phototransistor design is expected to yield bandwidths ~ 25 GHz for HBTs with 0.5 micron collector thicknesses. Reduced collector width will significantly increase this bandwidth. This performance would represent a considerable increase in the state-of-the-art and is thus expected to be applicable to a wide variety of high-performance OEIC receiver applications.

2.5 Intrinsic HBT Process for Ultra-High Speed HBTs and Photoreceivers

A number of key elements of a novel HBT process invented by RTI were also developed under this program. This process, termed symmetric intrinsic device processing, provides for the virtual elimination of extrinsic device capacitance in vertical structures. This process is expected to yield a substantial improvement in state-of-the-art AlGaAs/GaAs HBT performance with simultaneous f_T and f_{max} greater than 200 GHz and 500 GHz, respectively, for a one-micron emitter. This process also provides for

replacement of the native GaAs substrate with an application specific surrogate substrate. This feature will provide a number of performance advantages for applications including high efficiency power amplifiers, quasi-optical power combining and integrated mm-wave systems. Furthermore, this process is well suited for implementation of the laterally incident HBT photodetector described above. The combination of these two inventions will result in ultra-high frequency optical receivers by providing for an optimum combination of minimum device parasitics for high speed and maximum optical cross section for high sensitivity.

Three of the four major technical problems to realizing these high performance HBT devices with this process were solved in this program. These problems were 1) the attachment of a surrogate substrate, 2) symmetric, backside alignment of the collector metalization to the frontside emitter alignment and 3) development of a low resistivity collector contact without compromising the bond between the surrogate substrate and HBT emitter interconnect. The remaining major technical barrier to be solved before this exceptional performance can be realized is degradation of the emitter-base junction during attachment of the surrogate substrate.

2.6 High Injection HBT for Wideband Fiber Optic Links

A new type of HBT device capable of high performance optical modulation, optical detection and laser action was also invented on this program. This device is called the high injection heterojunction bipolar transistor (HIHBT). The operating principle of this device involves bandgap engineering of a potential well in the base near the emitter-base junction which significantly increases the injected minority carrier base concentration and allows inversion to be obtained. Performance estimates of optical modulation in a InP-based HIHBT predict that microwave fiber optic links with > 0 dB of link gain at > 50 GHz can be achieved.

3.0 LIST OF PUBLICATIONS

3.1 *Pnp HBT with 66 GHz F max*, D. B. Slater, Jr., P.M. Enquist, J.A. Hutchby, A. S. Morris, and R.J. Trew, IEEE Electron Device Letters, vol. 15, No. 3, March 1994.

3.2 *Low Resistance GaAs Based HBTs Without InGaAs Caps*, D.B. Slater, Jr., P.M. Enquist, J.A. Hutchby, A.S. Morris, R.J. Trew, IEEE Electron Device Letters, vol. 15, No 5, May 1994.

3.3 *Heterojunction Bipolar Transistors for Millimeter Wave and Photonic Applications*, A. Paolella, S. Malone, W. Van Meerbeke, P. Enquist, and D. Slater, 12th Annual Ben Franklin Symposium, IEEE, MTT, AP sponsored, Philadelphia, PA, May 6, 1994.

3.4 *Analytical Model with Empirical Verification for Heterojunction Bipolar Transistors Under Illumination*, D. B. Slater, Jr.,L.E.M. deBarros, Jr., A. Paolella, P. Herczfeld and P. Enquist, Proceedings of the 1995 IEEE MTT-S Microwave Symposium.

3.5 *Modeling the Photoresponse of Heterojunction Bipolar Transistors*, L.E.M. deBarros, Jr., A. Paolella, P. Herczfeld and P. Enquist, 25th European Microwave Conference, Bologna, Italy (1995).

3.6 *Performance Evaluation of Heterojunction Bipolar Transistors Designed for High Optical Gain*, P. Enquist, A. Paolella, A.S. Morris, F.E. Reed, L. deBarros, Jr., A.J. Tessmer and J.A. Hutchby, Proceedings of the 1995 IEEE Cornell Conference, Ithaca, NY, Aug. 1995.

4.0 LIST OF INVENTIONS

High-speed Heterojunction Bipolar Transistor Photodetector

High-Injection Heterojunction Bipolar Transistor (HIHBT)

5.0 LIST OF PARTICIPATING SCIENTIFIC PERSONNEL

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